

PHYSICAL
SCI. LIB.

TN

24

C3

A33

NO. 133



Digitized by the Internet Archive
in 2012 with funding from
University of California, Davis Libraries

<http://archive.org/details/claymineralogysl133borc>

24
3
33
133
S

PHYSICAL
SCIENCE

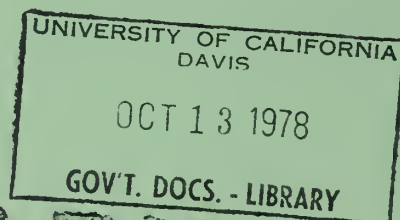
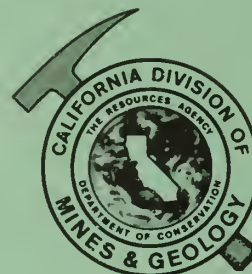
PHYSICAL SCI. LIB.

CLAY MINERALOGY AND SLOPE STABILITY

1977

CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 133



UC LIBRARY



STATE OF CALIFORNIA
EDMUND G. BROWN JR.
GOVERNOR

THE RESOURCES AGENCY
HUEY D. JOHNSON
SECRETARY FOR RESOURCES

DEPARTMENT OF CONSERVATION
PRISCILLA C. GREW
DIRECTOR

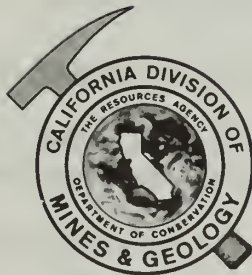
DIVISION OF MINES AND GEOLOGY
THOMAS E. GAY JR.
STATE GEOLOGIST

SPECIAL REPORT 133

CLAY MINERALOGY AND SLOPE STABILITY

By GLENN A. BORCHARDT

1977



CALIFORNIA DIVISION OF MINES AND GEOLOGY
1416 Ninth Street, Room 1341
Sacramento CA 95814

UCS LIBRARY

CONTENTS

ABSTRACT	iv
INTRODUCTION	1
ACKNOWLEDGMENTS	1
MATERIALS	1
METHODS	1
Particle-Size Distribution	1
Atterberg Limits	5
Shear Strength	5
X-ray Diffraction of Clay Fractions	9
RESULTS AND DISCUSSION	10
Water <i>versus</i> Shear Strength	10
Effect of organic matter	10
Correlations Between Physical Parameters	10
Clay Mineralogy	11
Correlations with physical parameters	11
Correlations among clay minerals	12
Expansive soils	13
Landslides	13
Summary of the clay mineralogy of landslides	14
Monitoring unstable slopes	14
CONCLUSIONS	14
REFERENCES	15

ILLUSTRATIONS

Table 1. Soils and sedimentary rocks sampled along coastal California ..	2
Table 2. Physical parameters and qualitative x-ray diffraction for clay mineralogy of soils and sedimentary rocks	6
Table 3. Correlation coefficients for physical parameters of soils and sedimentary rocks (n = 127 samples)	11
Table 4. Coefficients for correlations between physical parameters and estimates of clay mineral contents (n = 127 samples)	11
Table 5. Correlations among estimates of clay mineral contents (n = 127 samples)	12
Table 6. Relative abundance of minerals in clay fractions extracted from 66 landslide samples of coastal California	14

Illustrations (continued)

- Figure 1. Precision of the curve of % water *versus* the log of the shear strength for sample 485/72 5
- Figure 2. Water content *versus* shear strength for a landslide soil containing smectite clay (549/72), soil derived from Lambert siltstone containing large amounts of silt and organic matter (534/72), and a Miocene mudstone containing predominantly silt and kaolinite clay (34/73) 9
- Figure 3. Relationship between the plasticity index and smectite 12
- Figure 4. Unified soil classification for 66 landslide samples 13

ABSTRACT

One hundred twenty-seven landslide, soil, and sedimentary rock samples from the Coast Ranges of California were analyzed for clay mineralogy, shear strength, plasticity, and clay content to relate these parameters to the stability of slopes. The plasticity index was directly related to smectite content (beidellite and montmorillonite) in the samples ($r = 0.77$). Other measures of cohesion, such as the steepness of water content *versus* shear strength curves, were also related to soil expansion and smectite content. Sixty-six samples known to represent landslides had widely ranging physical properties, none of which could be used to distinguish them from samples from stable slopes. Ninety percent of the landslides had smectite, which was particularly abundant in 60 percent of them. Although five landslide samples were void of smectite, they contained vermiculite, the other expanding clay mineral. Traces of nonexpanding clay minerals, mica and chlorite, were found in over two-thirds of the landslides. Kaolinite, however, was not found in 60 percent of the landslides. Slopes containing smectite-free kaolinite appeared to be stable. These were represented by Tertiary mudstone on the west side of the San Andreas fault.

CLAY MINERALOGY AND SLOPE STABILITY

By GLENN A. BORCHARDT¹

INTRODUCTION

Cost estimates of damage from landslides average over \$300 million each year in California (Alfors and others, 1973). In an effort to avoid some of this damage, the California Division of Mines and Geology is preparing geology and slope stability maps for rapidly urbanizing areas of the state. Geologists working in this program have collected numerous soil and sedimentary rock samples that represent both stable and unstable formations in the Coast Ranges. These samples were analyzed for shear strength, plasticity, and particle-size distribution as a supplement to the field work. The data give a general idea of the physical properties of the soils and enable us to compare those properties with the clay mineral contents determined by x-ray diffraction. Certain of these clay minerals, namely, smectites (formerly the montmorillonite group), are primarily responsible for high plasticity, adsorption of great quantities of water, slow drainage, and subsequent loss of shear strength in unstable soils. Consequently, those geologic formations containing, or weathering to, smectite must receive special attention when preparing slope stability maps.

ACKNOWLEDGMENTS

This study would not have been possible without the help of the following Division geologists who contributed samples and advice concerning landslides: C.F. Armstrong, C.C. Bishop, G.B. Cleveland, E.W. Hart, M.E. Huffman, R.D. Knox, R.V. Miller, P.K. Morton, S.J. Rice, and T.H. Rogers. Laboratory personnel involved in the analysis of samples were: H.H. Majmundar, E.W. Deaneau, Lydia Lofgren, C.B. Smith, S.S. Tsuchiya, Bill Wong, Audrey Dere, John Hui, Dennis Lee, and Bryan Tam. The help of D.A. Rodgers concerning computer applications is also appreciated.

MATERIALS

One hundred twenty-seven samples from soils and sedimentary rocks (table 1) were collected by Division geologists to determine soil and slope stability (Huffman, 1972;

Huffman and others, 1973; Rogers and Armstrong, 1973; Bishop and others 1973; Rice, 1973). Many of these samples were taken from the headwall (for example, no. 21/73), toe (19/73), or slide plane (516/72) of recently active landslides. Others represent unstable rock (574/72) or unstable soils (520/72) formed from otherwise stable rock. Also included are samples of fault gouge (552/72), alluvium (574/72), and generally stable formations (534/72). The samples are all relatively unconsolidated material, and as expected for samples of diverse origin, the clay contents and physical properties vary widely. In some respects, the samples could be considered representative of surficial materials that the geologists thought important for understanding slope stability in the region.

METHODS

The tests described are used to determine the physical properties that affect soil stability (Borchardt, 1977b). Moisture changes and their effect upon shear strength are of primary importance for landslide studies. Other factors such as the percentage of clay, liquid limit, plasticity index, and clay mineralogy can help determine the type of soil stability problem likely to occur. Most landslides exhibit properties intermediate between two extreme types: cohesive slides and noncohesive slides.

Cohesive slides generally occur in clayey materials after long periods of rainfall. This is because the shear strength decreases slowly with large increases in water content aided by extremely slow drainage. Liquid limits and plasticity indices of cohesive slides are high.

Noncohesive slides occur in coarse, sandy materials during short periods of intense rainfall. This is because the shear strength decreases rapidly with only slight increases in water content even though drainage is normally rapid. Liquid limits and plasticity indices of these soils are usually low.

Particle-Size Distribution

The particle-size distribution was determined with the hydrometer method (Day, 1965) by using sodium metasilicate instead of calgon. The samples were dispersed

¹Soil Mineralogist, California Division of Mines and Geology

Table 1. Soils and sedimentary rocks sampled along coastal California.

LAB. NO.	NAME OF MATERIAL	FIELD NO.	LOCATION	COUNTY	LATITUDE DEG. MIN.	LONGITUDE DEG. MIN.
201/72	LOS OSOS CL	72B001	CROCKETT	CONTRA COSTA	38 2.03	122 12.39
202/72	LOS OSOS CL	72B002	RHEEM VALLEY	CONTRA COSTA	37 51.25	122 6.77
203/72 *	LOS OSOS CL	72B003	RHEEM VALLEY	CONTRA COSTA	37 51.25	122 6.70
204/72 *	LOS OSOS CL	72B004	RHEEM VALLEY	CONTRA COSTA	37 51.25	122 6.70
205/72 *	LOS OSOS CL	72B005	RHEEM VALLEY	CONTRA COSTA	37 51.25	122 6.63
206/72 *	CLAY SLIDE	SP-1	TOLAY CREEK	SONOMA	38 8.84	122 27.18
207/72	SHALE	QYR-1	QUARRY ROAD	SANTA CLARA	37 16.22	122 2.81
208/72	SHALE	STC-1	STEVENS CREEK	SANTA CLARA	37 18.38	122 4.12
411/72 *	KJF SOIL	72C001	WILLOW CREEK	SAN LUIS OBISPO	35 26.70	120 2.21
412/72 *	KU SHALE	72C002	FISCALINI CREEK	SAN LUIS OBISPO	35 32.01	121 3.23
413/72 *	KU SHALE	72C003	HARMONY VALLEY	SAN LUIS OBISPO	35 30.57	121 1.11
414/72 *	KJF SHALE	72C004	CAYUCOS	SAN LUIS OBISPO	35 26.80	120 3.51
415/72 *	KJF SHALE (SERP)	72C005	OLD CREEK	SAN LUIS OBISPO	35 26.76	120 3.45
416/72 *	KJF SHALE	72C006	WHALE ROCK	SAN LUIS OBISPO	35 26.09	120 3.04
417/72 *	MM BENT. SHALE	72C007	SANTA MANUELA SCH	SAN LUIS OBISPO	35 11.09	120 28.83
418/72 *	MVP TUFF	72C008	MALLAGH LANDING	SAN LUIS OBISPO	35 10.60	120 42.96
420/72 *	KJF SERP. SOIL	72C010	CERRO ROMAULDO	SAN LUIS OBISPO	35 18.59	120 44.04
421/72 *	KJF SERP. SOIL	72C011	MORRO CREEK	SAN LUIS OBISPO	35 24.70	120 8.51
422/72 *	KJF SERPENTINE	72C012	MORRO CREEK	SAN LUIS OBISPO	35 24.82	120 8.23
423/72 *	KJF SERPENTINE	72C013	MORRO CREEK RES.	SAN LUIS OBISPO	35 25.01	120 7.80
424/72 *	KJF SERPENTINE	72C014	MORRO CREEK RES.	SAN LUIS OBISPO	35 25.04	120 7.77
425/72 *	PYL BEDROCK	72C015	BIG SANDY CREEK	SAN LUIS OBISPO	35 48.08	120 42.85
426/72 *	PYL SOIL	72C016	MCKAY	SAN LUIS OBISPO	35 47.55	120 42.99
427/72 *	QP BEDROCK	72C017	WHITLEY GARDENS	SAN LUIS OBISPO	35 39.25	120 30.78
428/72 *	QP BEDROCK	72C018	CHOLAME CREEK	SAN LUIS OBISPO	35 42.13	120 18.27
430/72 *	CONTROL SOIL	72C020	SAN JUAN CREEK	SAN LUIS OBISPO	35 31.60	120 35.24
431/72 *	KJF SERPENTINE	72C021	FROOM CREEK	SAN LUIS OBISPO	35 14.13	120 41.15
432/72	CAPISTRANO FM.	72C022	SAN CLEMENTE	ORANGE	33 26.05	117 37.81
433/72	PALM SPRING FM.	72C023	PALM SPRING	SAN DIEGO	32 55.29	116 12.92
434/72	RINCON FM. MUS.	72C024	RINCON POINT	VENTURA	34 22.55	119 28.58
435/72 *	OLIGOCENE SED.	72C025	VAQUERO FLAT	SAN LUIS OBISPO	35 1.01	120 21.06
461/72 *	LANDSLIDE CLAY	TC-117	TILDEN REG. PARK	CONTRA COSTA	37 54.33	122 15.19
462/72 *	LANDSLIDE CLAY	TC-145-1	WILDCAT CREEK	CONTRA COSTA	37 56.33	122 17.47
463/72 *	LANDSLIDE CLAY	TC-145-2	WILDCAT CREEK	CONTRA COSTA	37 56.33	122 17.47
464/72 *	LANDSLIDE CLAY	TC-149	WILDCAT CREEK	CONTRA COSTA	37 56.27	122 17.26
470/72	CLAY SHALE	72B010	SAN PABLO DAM RD.	CONTRA COSTA	37 55.24	122 14.33
472/72	CLAY SHALE	72B012	SAN PABLO DAM RD.	CONTRA COSTA	37 55.60	122 14.96
480/72 *	DIABLO CLAY	72B020	LEISURE LANE SPG.	CONTRA COSTA	37 57.43	122 17.50
491/72 *	DIABLO CLAY	72B021	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
492/72 *	DIABLO CLAY	72B022	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
493/72 *	DIABLO CLAY	72B023	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
484/72 *	DIABLO CLAY	72B024	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
485/72 *	DIABLO CLAY	72B025	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
494/72 *	DIABLO CLAY	72B034	LEISURE LANE GUL.	CONTRA COSTA	37 57.40	122 17.44
503/72 *	OLD LANDSIDE	72B043	CONGRESS SPG. QRY	SANTA CLARA	37 15.14	122 2.89
510/72 *	LANDSLIDE CLAY	72B050	ANTLER BARN SLIDE	SANTA CLARA	37 15.48	122 2.76

(continued)

Table 1 (continued)

LAB. NO.	NAME OF MATERIAL	FIELD NO.	LOCATION	COUNTY	LATITUDE DEG. MIN.	LONGITUDE DEG. MIN.
511/72 *	LANDSLIDE CLAY	72B051	ANTLER BARN SLIDE	SANTA CLARA	37 15.48	122 2.76
512/72	REDDISH SOIL	72B052	WATER TANK	SANTA CLARA	37 15.48	122 2.76
513/72 *	ROADSIDE SLIDES	72B053	STEVENS CK PARK	SANTA CLARA	37 15.72	122 4.21
514/72 *	ROADSIDE SLIDES	72B054	STEVENS CK RES.	SANTA CLARA	37 17.42	122 4.85
515/72 *	ROADSIDE SLIDES	72B055	MONTE BELLO ROAD	SANTA CLARA	37 17.76	122 5.30
516/72 *	LANDSLIDE CLAY	72B056	PIERCE RD SLIDE	SANTA CLARA	37 15.94	122 3.11
518/72 *	LANDSLIDE CLAY	72B058	PIERCE RD PASTURE	SANTA CLARA	37 15.65	122 3.13
520/72	GREENSTONE SOIL	72B060	MOODY ROAD	SANTA CLARA	37 21.51	122 9.82
534/72 +	LAMBERT SILT. SL	72B074	PETERS CREEK	SANTA CRUZ	37 17.09	122 9.03
536/72	FR. SHEARED SH	72B076	MONTE BELLO RIDGE	SANTA CLARA	37 18.04	122 6.73
537/72	FR. SHEARED SH	72B077	MONTE BELLO RIDGE	SANTA CLARA	37 18.04	122 6.73
538/72	FR. SHEARED SH	72B078	MONTE BELLO RIDGE	SANTA CLARA	37 18.04	122 6.73
542/72 *	MONTEREY SH SL	72B082	CAMINO HERMOSO	SANTA CLARA	37 20.75	122 6.59
543/72 *	MONTEREY SH SL	72B083	CAMINO HERMOSO	SANTA CLARA	37 20.75	122 6.59
547/72	ALLUVIAL CLAY	STC-10A	STEVENS CREEK	SANTA CLARA	37 18.51	122 3.97
548/72	ALLUVIAL CLAY	STC-10E	STEVENS CREEK	SANTA CLARA	37 18.51	122 3.97
549/72 *	LANDSLIDE CLAY	CB1	CIENEGA ROAD S.	SAN BENITO	36 47.28	121 24.18
550/72	CLAY	CB2	CIENEGA ROAD N.	SAN BENITO	36 47.67	121 24.41
551/72	CLAY	CB3	SARGENT	SANTA CLARA	36 55.35	121 32.75
552/72	FAULT GOUGE	CB4	SAN JUAN BATISTA	SAN BENITO	36 52.39	121 34.27
553/72	SC COLLUVIUM	50	BUCKHORN RANCH RD	SONOMA	38 24.73	123 5.80
554/72 *	TERRACE CLAY	64A	WRIGHT BEACH	SONOMA	38 23.57	123 5.53
555/72 *	SANDY CLAY	76A	COLEMAN VALLEY RD	SONOMA	38 22.15	123 3.60
556/72 *	SANDY CLAY	92A	PAY HILL ROAD	SONOMA	38 20.73	123 2.37
557/72 *	SHALE	93A	MT. ROSCOE	SONOMA	38 20.70	123 2.38
559/72	KJF ROCKS	140	GLEASON BEACH	SONOMA	38 23.32	123 5.00
560/72 *	CLAY COLLUVIUM	178	ESTERO LANE	SONOMA	38 19.13	122 59.47
561/72 *	SILTY CLAY	179	ESTERO LANE	SONOMA	38 19.13	122 59.47
562/72 *	GRAYISH BL. CLAY	1001	INVERNESS AVE.	SONOMA	38 22.22	122 39.13
563/72 *	GRAYISH PL. CLAY	1002	INVERNESS AVE.	SONOMA	38 22.20	122 39.13
564/72	SILTSTONE	1003	INVERNESS AVE.	SONOMA	38 22.23	122 39.13
565/72	CLAYEY SILTSTON	1004	LYNCH CREEK	SONOMA	38 16.77	122 36.98
566/72	SANDY CLAY	2001	HORSESHOE COVE E	SONOMA	38 36.62	123 21.73
567/72 +	MUDSTONE	2002	HORSESHOE COVE SE	SONOMA	38 36.43	123 21.67
568/72 +	MUDSTONE	2003	SALT POINT	SONOMA	38 34.67	123 19.55
569/72 *	BL. CLAY GOUGE	2004	FORT ROSS SW	SONOMA	38 30.05	123 12.92
570/72 *	SS AND CLAY	2005	TIMBER GULCH	SONOMA	38 29.90	123 12.43
571/72 *	BLACK CLAY	2006	RUSSIAN GULCH	SONOMA	38 28.88	123 10.13
1/73	BROWN SOIL L/S	NOS-2	BURDELL	MARIN	38 9.19	122 34.29
2/73	ANDESITE SOIL	NOS-4	BURDELL MT.	MARIN	38 9.03	122 34.42
3/73	LT. BROWN SOIL	NOS-5	ARROYO SAN JOSE	MARIN	38 3.66	122 33.19
4/73	BAY MUD	NOS-8	NW PACIFIC RR	MARIN	38 5.99	122 30.92
5/73	SCHIST SOIL	NOS-10	NOVATO VALLEY	MARIN	38 7.53	122 36.23
6/73	SCHIST SOIL	NOS-11	NOVATO VALLEY	MARIN	38 7.53	122 36.23
7/73	METAVOLCANIC SL	NOS-12	NOVATO CK. HEAD	MARIN	38 7.78	122 36.75

(continued)

Table 1 (continued)

LAB. NO.	NAME OF MATERIAL	FIELD NO.	LOCATION	COUNTY	LATITUDE DEG. MIN.	LONGITUDE DEG. MIN.
9/73 *	SCHIST L/S SOIL	NOS-13	HILL 967	MARIN	38 8.01	122 36.70
9/73 *	SCHIST L/S SOIL	NOS-14	DEER IS. SOUTH	MARIN	38 5.67	122 32.07
10/73 *	SCHIST L/S SOIL	NOS-15	DEER IS. NORTH	MARIN	38 6.20	122 32.16
11/73 *	ARKOSE SOIL	NOS-16	NOVATO BLVD.	MARIN	38 4.70	122 33.32
12/73 *	SCHIST SOIL	NOS-17	OLIVE ST. SCHOOL	MARIN	38 6.65	122 33.17
14/73 *	BLACK CLAY	NOS-19	SAN MARIN DRIVE	MARIN	38 7.55	122 35.05
15/73 *	CLAY	GIL-7	SANTA TERESA EX.	SANTA CLARA	37 0.0	121 30.00
16/73	SHEARED SHALE	266	FURLONG GULCH	SONOMA	38 24.87	123 5.12
17/73	SHALE GOUGE	269	SHELL BEACH	SONOMA	38 25.23	123 6.50
18/73	SERPENTINE CLAY	270	SHELL BEACH	SONOMA	38 25.03	123 6.30
19/73 *	LANDSLIDE CLAY	738001	DEER ISLAND SLIDE	MARIN	38 6.32	122 32.25
21/73 *	SCHIST SOIL L/S	738003	SAN MARIN DRIVE	MARIN	38 7.32	122 4.60
22/73 *	SCHIST SOIL L/S	738004	SAN MARIN DRIVE	MARIN	38 7.32	122 4.60
23/73 *	SCHIST SOIL L/S	738005	SAN MARIN DRIVE	MARIN	38 7.32	122 4.60
24/73 *	SCHIST SOIL L/S	738006	SAN MARIN DRIVE	MARIN	38 7.32	122 4.60
25/73 *	SCHIST SOIL L/S	738007	SAN MARIN DRIVE	MARIN	38 7.32	122 4.60
26/73	SERPENTINE SOIL	738008	SAN MARIN DRIVE	MARIN	38 7.63	122 35.05
28/73	SCHIST	NO. 56	LOGAN ST. 101 CUT	MARIN	38 6.47	122 33.72
29/73	GRAY CLAY SHALE	2007	HORSESHOE POINT	SONOMA	38 36.40	123 21.68
30/73	KA SILTSTONE	2008	FISHERMANS BAY	SONOMA	38 38.87	123 23.73
31/73 +	GERMAN RANCHO	2009	BENCHMARK 59	SONOMA	38 37.53	123 22.80
32/73	CLAY SEAM	2010	ROCKY POINT	SONOMA	33 37.90	123 23.13
33/73	MIOCENE MUDSTON	2011	FORT ROSS COVE	SONOMA	38 30.77	123 14.57
34/73	MIOCENE MUDSTON	2012	FORT ROSS MON.	SONOMA	38 30.63	123 14.30
66/73	LOS TRANCOS MBR	73-141	BONITA CANYON DRV	ORANGE	33 37.97	117 50.24
57/73	TOPANGO FM.	73-142	BONITA CANYON DRV	ORANGE	33 37.97	117 50.24
69/73	TOPANGO FM.	73-147	BONITA CANYON DRV	ORANGE	33 37.97	117 50.76
70/73	CLAY	73-163	LAGUNA CANYON RD.	ORANGE	33 37.97	117 45.47
71/73	VAQUEROS FM.	73-164	LAGUNA CANYON RD.	ORANGE	33 37.97	117 45.47
73/73	SANTIAGO FM..	73-175	SANTIAGO CAN. RD.	ORANGE	33 41.82	117 38.21
74/73	LA HABRA FM.	73-195	N EAST COYOT HILL	ORANGE	33 53.97	117 53.61
75/73	LA HABRA FM.	73-197	S DE SANTA ANA	ORANGE	33 53.97	117 54.65
76/73	COYOTE HILLS FM	73-201	W. BREA BLVD.	ORANGE	33 53.55	117 55.15
80/73	SESPE FM.	73-216	N LAGUNA CANYON	ORANGE	33 36.62	117 45.50
81/73	MONTEREY FM.	73-219	SW LAGUNA HILLS	ORANGE	33 35.77	117 42.86
82/73	MONTEREY FM.	73-223	S LAGUNA HILLS	ORANGE	33 35.77	117 42.86

1/ Laboratory number assigned to sample for detailed information available in the Geochemical Section, California Division of Mines and Geology.

* Landslide sample.

+ Stable soil or sedimentary rock containing smectite-free kaolinite.

for five minutes by using the ultrasonic water bath. This was followed by a mild hydrogen-peroxide treatment as an additional aid to dispersion. A Bouyoucos mixer was used to further disperse the samples, although future work will be done with the Iowa air-jet dispersion apparatus. This achieves even better segregation of individual clay particles while breaking fewer of the micaceous sand grains (Chu and Davidson, 1953). The temperature of suspensions was controlled at 25°C with the use of a water bath and an inexpensive temperature controller (Blue M Electric Company, Blue Island, Illinois). A few samples were impossible to disperse and were not included in the study. Values reported (table 2) are for < 2 mm material. Because other physical tests involve < 420 μm material, recalculations were necessary for direct comparisons of data.

Atterberg Limits

Liquid limits, plastic limits, and plasticity indices (table 2) were determined using standard methods (Sowers, 1965). A few soils, too sandy for plastic limit determinations, were not included in this study.

Shear Strength

A torsion vane shear testing device (Soiltest, Evanston, Illinois) was used to determine shear strength at various moisture contents between the liquid and plastic limits.

Shear tests were run in conjunction with the Atterberg limits. Samples were dried slightly after soil was removed for the liquid limit test. A shear vane reading was made directly in the liquid limit device after thorough mixing. About 10 grams of soil from the area of shear was placed into a tared weighing bottle and oven-dried at 110°C to determine moisture content. This was repeated for a duplicate analysis, and then the entire soil sample was dried with a fan blower while being mixed. At some point prior to reaching the plastic limit, two more shear vane readings and moisture determinations were made. The results were plotted on a graph of % H_2O versus the log of the shear strength in kilograms per square centimeter (and tons per square foot) (figure 1). Intercepts and slopes of shear curves were calculated after interpolating data beyond the liquid and plastic limits, assuming a linear logarithmic relationship (Kerr and Drew, 1969).

The intercept (B) of the shear curve was arbitrarily chosen as the water content at which the shear strength was 0.001 kg/cm^2 . The slope (M) is this value minus the water content at 1 kg/cm^2 . This slope is analogous to the "flow index" of Casagrande (1932). Samples with high amounts of expansible clays tend to have shear curves with high intercepts and high negative slopes (figure 2). Note that, under conditions of restricted drainage, a small increase in moisture causes a larger decrease in shear strength for nonexpansible clays like kaolinite than it does for expansible clays like smectite.

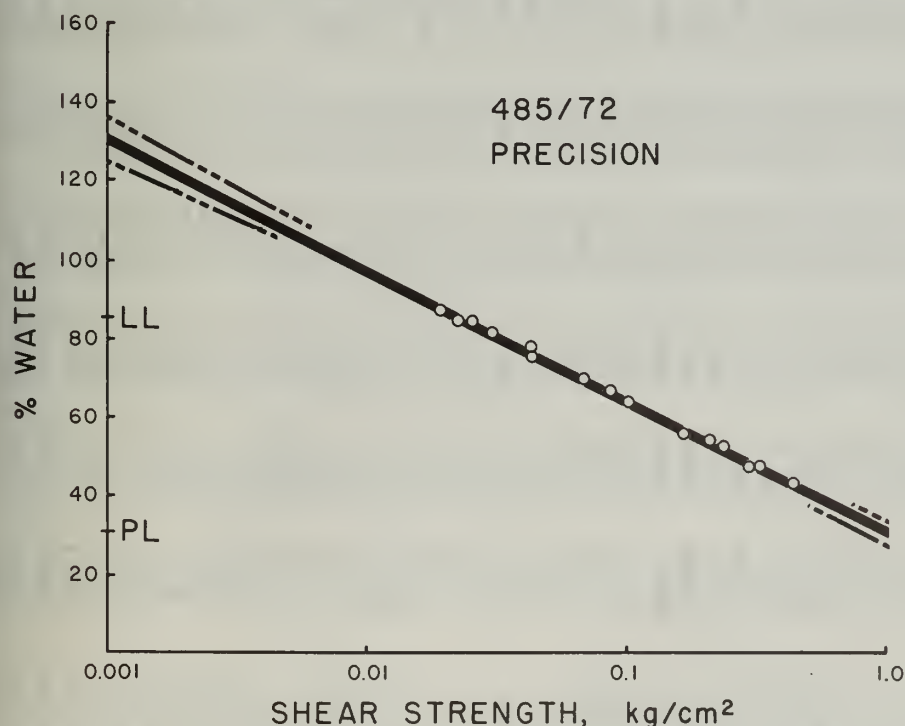


Figure 1. Precision of the curve of % water versus the log of the shear strength for Sample 485/72.

Table 2. Physical parameters and qualitative x-ray diffraction for clay mineralogy of soils and sedimentary rocks.

LAB. NO.	% SAND	% SILT & CLAY	LL	PL	PI	SHEAR $\bar{H}$	SHEAR $\bar{M}$	PH	%+420UM	ST	MT	BD	VR	CH	KL	MI	NC
201/72	8.4	56.8	34.8	45.5	23.6	21.9	55.5	33.7	6.20	3	3	2	2	1	0	1	0
202/72	30.6	42.7	26.7	35.2	20.1	15.1	49.8	28.0	5.55	3	3	3	0	1	0	1	0
203/72*	3.4	56.4	40.2	59.2	20.6	38.2	74.0	47.0	6.99	3	3	3	0	1	0	1	0
204/72*	0.3	69.5	30.2	49.0	24.8	24.2	61.0	33.2	7.25	3	3	3	0	1	0	1	0
205/72*	13.4	56.5	30.1	49.9	23.9	26.1	64.6	38.8	6.40	3	3	3	0	1	0	1	0
206/72*	9.1	48.5	42.4	54.0	18.0	36.0	93.5	74.9	7.80	3	3	3	0	1	0	1	0
207/72	1.2	61.3	37.6	51.7	21.8	30.0	79.2	55.0	7.20	3	3	2	0	1	1	1	0
208/72	12.4	28.8	58.8	68.8	19.6	49.2	90.0	70.5	7.45	3	3	2	0	2	0	1	0
411/72*	27.6	39.2	33.2	37.1	17.1	20.0	54.2	34.7	7.45	1	1	0	3	0	0	1	0
412/72*	18.2	45.1	36.7	48.2	22.2	26.0	58.0	30.2	6.90	3	3	3	0	1	1	0	0
413/72*	18.5	49.2	32.3	41.7	21.7	20.0	59.8	35.2	6.30	2	2	0	2	0	0	0	0
414/72*	29.5	47.5	23.0	24.0	15.9	8.1	29.5	13.5	7.75	0	0	0	2	2	3	2	0
415/72*	45.1	46.1	8.8	26.4	16.3	10.1	34.0	15.5	7.30	1	1	1	1	1	2	1	0
416/72*	12.1	43.6	44.3	46.8	18.6	28.2	77.0	58.5	7.75	1	1	1	2	1	2	1	0
417/72*	16.7	44.9	38.4	79.1	29.4	49.7	107.0	64.2	1.85	3	3	0	0	0	0	0	0
418/72*	28.1	39.1	32.8	125.2	56.6	68.6	130.0	60.5	7.35	3	3	0	0	0	0	0	0
420/72*	30.0	38.7	31.3	37.4	19.6	17.8	44.6	22.6	6.30	2	1	2	2	0	0	1	0
421/72*	13.8	43.5	42.7	44.6	19.3	25.3	61.4	38.6	7.87	1	1	1	2	1	2	1	0
422/72*	29.8	46.0	24.2	38.7	19.3	19.4	52.4	27.4	7.50	2	2	1	2	1	1	1	0
423/72*	35.0	38.1	26.9	47.4	20.8	26.6	66.8	42.8	6.65	3	3	1	1	1	1	1	0
424/72*	58.9	29.4	11.7	31.8	20.3	11.5	52.4	32.9	7.40	3	3	0	0	0	0	0	0
425/72*	39.0	41.5	14.5	35.6	19.1	16.5	46.2	26.0	7.50	3	3	0	1	0	1	1	0
426/72*	42.4	41.6	16.0	27.4	15.2	12.2	34.5	16.5	7.25	2	2	1	1	1	1	1	0
427/72*	51.7	37.4	10.9	30.5	17.9	12.6	60.0	53.0	7.15	2	2	1	0	0	1	1	0
428/72*	14.0	53.5	32.5	44.6	18.2	26.4	65.5	46.3	0.0	2	2	1	0	1	2	1	0
429/72	60.5	33.0	6.5	20.8	19.0	1.8	26.0	9.5	7.45	3	3	0	0	0	0	1	0
431/72*	37.7	45.2	17.1	37.7	17.7	20.0	53.0	32.2	7.55	3	3	2	1	2	2	0	0
432/72	7.6	58.3	34.1	43.6	24.5	19.1	71.5	43.5	2.50	3	3	0	0	0	1	1	0
433/72	59.8	30.2	10.0	23.4	21.8	1.6	29.7	10.9	8.05	3	3	0	0	0	1	1	0
434/72	2.5	39.1	58.4	33.7	25.4	8.3	0.0	0.0	0.02	0	0	0	0	0	0	0	3
435/72*	24.3	56.7	19.0	35.3	20.4	14.9	46.4	23.9	7.36	3	3	0	0	0	1	1	0
461/72*	61.8	32.2	6.0	33.0	30.4	2.6	47.0	24.5	6.55	3	2	3	0	0	0	0	0
462/72*	33.3	55.7	11.0	31.5	14.3	17.2	48.0	30.5	7.70	3	3	0	0	2	0	1	0
463/72*	8.0	59.8	32.2	49.8	27.7	22.1	67.0	42.5	7.45	3	3	0	3	0	0	1	0
464/72*	1.9	63.1	35.0	50.5	23.0	27.5	68.2	43.4	7.25	3	0	3	0	1	0	1	0
470/72	3.9	88.6	7.5	47.8	33.6	14.2	68.5	40.0	7.40	3	3	0	0	2	0	1	0
472/72	26.0	56.0	18.0	53.0	29.1	23.9	69.0	34.0	7.20	3	3	3	0	1	0	1	0
480/72*	19.9	40.1	40.0	60.0	21.8	38.2	81.0	48.5	6.65	3	0	3	0	1	1	1	0
481/72*	13.8	48.7	37.5	58.0	24.1	33.9	73.0	42.0	5.60	2	2	2	0	1	0	1	0
482/72*	15.0	45.7	39.3	47.3	22.8	24.5	68.5	43.0	5.50	2	2	2	1	1	0	0	0
483/72*	12.6	54.9	32.5	55.8	19.5	36.3	81.0	55.5	5.95	2	2	2	1	1	0	0	0
484/72*	10.2	47.8	42.0	59.0	22.6	36.4	91.5	69.0	6.90	2	2	2	0	1	0	1	0
485/72*	1.3	48.7	50.0	86.9	30.8	56.1	116.0	83.5	7.45	3	3	2	0	0	0	1	0
494/72*	1.1	54.1	44.8	93.0	30.0	63.0	124.0	95.5	7.75	3	3	2	0	1	0	1	0
503/72*	12.3	45.7	42.0	58.5	19.2	39.3	84.8	61.3	7.45	3	1	3	0	1	1	1	0
510/72*	7.5	54.5	38.0	49.5	22.2	27.3	65.5	33.5	6.60	3	3	3	0	1	1	1	0
511/72*	20.8	47.4	31.8	37.5	19.0	18.5	54.8	32.8	6.40	3	3	3	0	1	1	1	0

(continued)

Table 2 (continued)

LAB. NO.	NO. 1/2	SAND	SILT	CLAY	LL	PL	PI	SHEAR B	SHEAR M	PH	Σ+420UM	ST	QUALITATIVE ESTIMATES 2/									
													MT	BD	VR	CH	KL	MI	NC			
512/72		40.1	33.7	26.2	35.0	19.8	15.2	47.3	23.3	6.25	10.0	3	0	3	2	1	0	0	0			
513/72*		31.5	38.3	30.2	37.0	19.0	18.0	49.0	28.5	6.15	10.0	3	0	3	1	1	0	1	0			
514/72*		40.4	31.6	28.0	32.5	17.9	14.6	47.4	27.4	6.75	13.5	3	0	3	1	2	0	1	0			
515/72*		40.5	30.5	29.0	43.8	20.6	23.2	58.0	37.0	6.85	18.0	1	0	1	3	1	0	1	0			
516/72*		2.0	29.7	68.3	123.3	46.9	76.4	130.0	95.5	7.90	0.8	3	0	3	0	1	0	1	0			
518/72*		2.1	46.9	51.0	75.3	28.2	47.1	103.0	73.5	6.80	0.5	3	0	3	3	1	0	0	0			
520/72		33.2	40.1	26.7	47.2	25.1	22.1	60.5	32.0	6.35	5.2	3	0	3	0	0	0	0	0			
534/72+		24.4	63.5	12.1	75.9	64.0	11.9	83.2	71.7	4.90	14.0	0	0	0	0	0	1	1	0			
536/72		42.8	36.2	21.0	33.9	23.1	10.8	42.4	23.4	6.10	25.5	0	0	0	3	0	0	1	0			
537/72		35.1	31.1	33.8	42.1	22.2	19.9	60.6	40.6	5.95	22.0	0	0	0	3	0	0	1	0			
538/72		46.9	29.9	23.2	37.8	22.5	15.3	48.0	22.0	5.70	34.0	0	0	0	3	0	0	1	0			
542/72*		25.8	36.2	38.0	53.5	26.0	27.5	69.5	35.0	6.80	12.0	3	0	3	0	0	0	0	0			
543/72*		11.1	36.7	52.2	63.3	24.6	38.7	84.0	50.0	6.45	5.0	3	0	3	0	0	0	0	0			
547/72		4.7	42.6	52.7	71.2	22.8	48.4	88.5	57.5	7.50	0.3	3	3	3	0	0	0	0	0			
549/72		5.9	49.7	44.4	60.5	19.7	40.8	83.5	60.3	7.40	1.0	3	3	3	0	0	0	0	0			
549/72*		3.7	41.9	54.4	125.2	30.7	94.5	161.0	128.5	8.00	0.2	3	3	3	0	0	1	1	0			
550/72		14.2	61.6	24.2	57.3	23.9	33.4	87.6	63.6	7.65	0.5	3	3	3	0	0	1	0	0			
551/72		1.1	71.4	27.5	50.0	23.6	26.4	66.6	34.8	7.60	0.0	2	2	1	1	1	2	0	0			
552/72		1.6	43.1	55.3	97.9	25.8	72.1	144.0	126.0	7.65	0.0	3	3	0	1	1	3	1	0			
553/72		34.2	33.8	32.0	37.8	21.7	16.1	52.5	32.5	6.20	6.5	1	0	1	3	0	0	1	0			
554/72*		40.1	27.9	32.0	48.0	22.3	25.7	67.4	47.4	5.70	4.5	1	0	1	3	0	0	1	0			
555/72*		27.2	39.3	33.5	41.0	18.2	22.8	58.0	37.5	6.45	3.2	1	0	1	3	0	0	1	0			
556/72*		39.6	32.4	28.0	30.3	16.9	13.4	44.8	28.0	5.85	9.0	1	0	1	2	0	2	1	0			
557/72*		49.6	36.6	14.8	37.1	24.3	12.8	53.0	30.0	6.20	36.7	0	0	0	3	0	0	2	0			
559/72		57.4	33.1	9.5	27.2	17.2	10.0	37.0	19.0	7.80	41.5	0	0	0	1	1	2	1	0			
560/72*		12.0	74.1	13.9	37.3	24.6	12.7	46.0	18.5	6.20	0.5	0	0	0	2	0	0	1	1			
561/72*		8.1	69.7	22.2	41.5	22.8	18.7	56.0	35.5	5.45	0.2	0	0	0	2	0	0	1	0			
562/72*		19.4	37.7	42.9	65.5	16.8	48.7	94.0	71.5	7.50	9.0	3	0	3	1	0	1	0	0			
563/72*		18.8	45.0	36.2	57.5	18.3	39.2	76.0	52.5	6.00	7.5	2	1	2	1	0	1	0	0			
564/72		14.6	78.6	6.8	37.0	27.5	9.5	54.0	31.2	6.85	0.5	2	1	2	1	0	1	1	0			
565/72		22.1	66.4	11.5	35.8	18.2	17.6	67.8	44.4	7.65	0.7	2	2	0	0	1	0	1	0			
566/72		62.0	25.5	12.5	25.0	19.5	5.5	54.0	44.5	5.65	25.0	0	0	0	1	2	0	1	0			
567/72+		10.6	69.4	20.0	35.3	25.0	10.3	44.0	20.8	3.90	2.0	0	0	0	1	0	3	1	0			
568/72+		12.6	63.9	23.5	38.3	26.5	11.8	50.5	26.9	5.35	4.0	0	0	0	1	0	3	1	0			
569/72*		23.0	43.0	34.0	41.8	15.2	26.6	77.0	70.0	7.60	9.0	0	0	0	0	2	0	1	0			
570/72*		42.0	42.5	15.5	36.0	24.8	11.3	55.0	33.0	6.30	16.5	1	1	1	0	1	0	1	0			
571/72*		38.7	44.8	16.5	30.5	16.2	14.3	59.5	49.0	7.40	23.5	2	0	2	0	2	0	1	0			
1/73		44.9	36.6	18.5	56.5	33.7	17.8	52.0	21.0	7.25	20.8	0	0	0	0	0	0	0	3			
2/73		22.2	47.6	30.2	36.3	29.6	6.7	44.5	17.5	5.10	7.0	1	0	1	1	0	3	1	1			
3/73		25.0	55.0	20.0	28.9	25.7	3.2	38.8	17.3	5.20	11.0	1	0	1	1	0	2	2	1			
4/73		0.2	44.4	53.6	72.3	37.0	35.3	82.4	40.4	4.30	0.0	3	0	3	1	1	1	1	0			
5/73		36.3	39.2	24.5	34.7	20.7	14.0	49.5	28.0	6.40	21.0	2	0	2	3	1	1	0	0			
6/73		18.1	48.1	33.8	55.7	26.6	29.1	76.0	37.5	7.05	5.0	3	0	3	0	3	0	0	0			
7/73		56.9	22.6	20.5	38.9	24.5	14.4	49.0	20.0	6.00	43.5	3	0	3	2	0	0	1	0			
8/73*		43.2	33.8	23.0	38.9	24.7	14.2	54.5	31.5	5.95	20.0	3	0	3	2	1	1	1	0			
9/73*		44.1	37.1	18.8	31.5	22.5	9.0	42.8	22.8	6.00	26.5	1	0	1	1	2	2	1	0			
10/73*		41.4	50.6	8.0	32.5	26.6	5.9	54.0	39.0	7.95	10.8	3	0	3	0	3	0	0	0			
11/73		32.0	50.8	17.2	23.3	20.4	2.9	31.0	14.5	5.95	2.5	0	0	0	0	1	1	1	2			

(continued)

(continued)

Table 2 (continued)

LAB. NO.	% SAND	% SILT	% CLAY	LL	PL	PI	SHEAR B	SHEAR M	PH	%+420UM	ST	MT	RD	VP	CH	KL	MI	NC
12/73*	20.4	27.4	52.2	63.3	30.6	32.7	85.0	51.5	5.00	8.8	1	0	1	3	0	0	1	0
14/73	11.2	34.3	54.5	88.1	27.5	60.6	104.0	63.5	7.75	3.5	3	0	3	0	2	1	0	0
15/73*	26.0	40.8	33.2	44.0	18.0	26.0	60.5	39.0	6.85	2.0	3	0	3	0	1	0	0	0
16/73	57.8	31.2	11.0	17.0	12.6	4.4	31.0	24.5	7.60	30.0	0	0	0	1	3	0	3	0
17/73	24.6	52.4	23.0	23.5	16.3	7.2	37.5	26.5	7.00	8.5	0	0	0	0	3	0	3	0
19/73	30.9	49.0	20.2	46.2	32.4	13.8	77.5	63.0	7.60	9.5	3	0	3	0	3	0	0	0
19/73*	8.5	71.7	19.8	55.0	47.3	7.7	85.0	63.5	7.70	0.3	3	0	3	0	2	0	0	0
21/73*	37.4	42.6	20.0	29.4	27.8	1.6	35.5	11.0	5.80	16.0	1	0	1	1	1	2	1	0
22/73*	43.2	39.3	17.5	31.2	27.5	3.7	40.5	18.7	5.95	16.0	3	0	3	2	0	2	1	0
23/73*	39.3	39.9	20.8	30.5	24.2	6.3	36.5	13.5	6.25	16.0	3	0	3	2	0	2	1	0
24/73	75.0	19.5	5.5	28.2	27.2	1.0	36.0	13.0	6.80	44.0	2	0	2	3	0	1	2	0
25/73*	36.1	29.9	34.0	43.5	25.1	18.4	55.0	32.7	5.95	13.3	3	0	3	2	1	1	1	0
26/73	39.7	25.7	34.6	61.3	35.2	26.1	71.5	29.0	6.85	11.0	1	0	1	0	0	0	0	1
28/73	67.1	27.4	5.5	18.5	17.4	1.1	33.0	21.5	7.80	38.0	0	0	0	0	3	0	3	0
29/73	3.6	79.4	17.0	37.8	27.4	10.4	54.5	31.0	3.65	0.0	0	0	0	1	1	3	1	0
30/73	65.8	26.7	7.5	24.3	20.7	3.6	38.0	18.5	6.38	48.5	1	0	1	1	0	0	1	1
31/73+	31.1	56.1	12.8	35.7	31.8	3.9	43.5	16.5	4.45	7.5	0	0	0	1	0	2	1	0
32/73	14.1	59.4	31.0	47.3	27.7	19.6	69.0	45.5	6.10	4.0	1	0	1	1	0	2	1	0
33/73	30.5	53.5	16.0	26.8	21.7	5.1	36.5	15.5	5.45	10.0	1	0	1	0	0	3	1	0
34/73	48.3	40.5	11.2	23.5	17.7	5.8	31.5	14.5	7.40	28.8	0	0	0	1	1	3	0	0
66/73	22.8	59.5	22.8	41.9	26.9	15.0	62.0	41.0	7.45	3.0	2	0	2	0	3	0	2	0
67/73	54.7	34.7	10.6	28.4	23.3	5.1	43.5	25.5	7.70	14.5	2	0	2	0	3	0	1	0
69/73	16.2	64.8	19.0	56.0	32.2	23.8	88.2	70.2	7.72	0.5	2	2	1	0	2	0	1	0
70/73	73.0	22.2	4.8	20.6	0.0	0.0	40.8	29.8	7.85	17.0	3	3	1	0	0	0	1	0
71/73	16.7	70.8	12.5	37.1	24.4	12.7	54.0	34.8	7.57	1.5	3	3	0	0	0	1	1	0
73/73	37.1	46.7	16.2	34.3	16.8	17.5	45.8	26.8	7.05	16.0	2	2	2	0	0	2	1	0
74/73	16.2	50.8	33.0	64.1	23.4	40.7	74.5	32.0	7.35	1.0	3	3	1	0	0	0	1	0
75/73	64.4	18.8	16.8	26.5	23.8	2.7	38.8	15.0	7.15	8.0	3	0	3	0	0	0	1	0
76/73	10.3	71.2	18.5	56.7	27.1	29.6	71.0	38.0	7.05	2.0	3	0	3	1	0	0	0	0
80/73	13.7	55.3	31.0	45.8	19.4	26.4	70.0	48.0	6.20	4.0	1	0	1	1	0	2	1	0
91/73	3.8	55.2	41.0	104.0	43.5	60.5	129.5	76.0	6.25	0.7	3	0	3	0	0	0	1	0
92/73	6.8	70.2	23.0	79.8	44.9	34.9	117.4	75.2	6.22	0.5	3	3	0	0	0	0	2	0

L/ Laboratory number assigned to sample for detailed information available in the Geochemical Section, California Division of Mines and Geology.

* Landslide sample.

+ Stable soil or sedimentary rock containing smectite-free kaolinite.

% SAND (2000-63 μ m), % SILT (63-2 μ m), % CLAY (less than 2 μ m) based upon the weight of the less than 2 mm fraction, LL (liquid limit): the moisture content at which a soil will change from plastic flow to liquid flow, PL (plastic limit): the moisture content at which a soil begins plastic flow, PI (plasticity index): LL - PL, SHEAR B: intercept (at 0.001 kg/cm²) of the % water versus shear strength curve, SHEAR M: negative slope of the % water versus shear strength curve (% water per kg/cm²), PH: pH of the soil-water paste, and %+420UM: percentage of sample between 2000 and 420 μ m. Used to recalculate the amount of clay and relative effects of clay minerals upon the less than 420 μ m material used for physical tests.

2/ Qualitative estimates: 0 = not detectable, 1 = trace amount present, 2 = moderate amount present, and 3 = abundant.

ST: (smectite) group of expanding clay minerals formerly called "montmorillonite", MT: (montmorillonite) one of the smectites,

BD: (beidellite) one of the smectites, VR: (vermiculite) an expanding clay mineral, CH: (chlorite), KL: (kaolinite),

MI: (mica), NC: (noncrystalline or amorphous material).

X-ray Diffraction of Clay Fractions

Clay fractions ($<2\ \mu\text{m}$) were obtained from the samples dispersed with sodium metasilicate. Approximately 0.7 gram (g) of sodium metasilicate is added to each 50 g of soil sample during the particle-size analysis. This small amount of sodium metasilicate or its reaction products produced no detectable interference with x-ray diffraction analysis. Calgon (Na_3PO_4) was not used as a dispersant because it reacts with the clay fraction to a greater degree than sodium metasilicate.

Magnesium-saturated clay ($<2\ \mu\text{m}$) samples were used to prepare slides by the smear-on-paste technique (Theisen and Harward, 1962). The degree of pressure required to produce a smooth film of clay varies from sample to sample. Therefore, a 15 cm flexible plastic rule was used instead of a spatula for spreading the paste. Slides were air-dried one hour, placed in a 54% relative-humidity chamber overnight, and x-rayed in a controlled 54% relative-humidity environment. Mica was qualitatively estimated from the 10-Angstrom (A) peak. Next, the sample was heated at 110°C for two hours in glycerol

vapor (Brown and Farrow, 1956) which was then allowed to condense onto the sample overnight. Another Mg-saturated sample was heated at 60°C for two hours in ethylene glycol vapor, which was then allowed to condense overnight. X-ray patterns for ethylene-glycol-treated slides of montmorillonite and beidellite were identical, showing expansion to about 17A. "Beidellite" was identified by its resistance to expansion when solvated with glycerol vapor (Harward and Brindley, 1964).

Potassium-saturated slides were similarly prepared and heated to 110°C , 300°C , and 550°C . Vermiculite was identified by collapse of 14A peaks to 10A after K saturation, drying at 110°C , and x-raying at 0% relative humidity. Kaolinite was identified (in the absence of a 14A peak) by the disappearance of the 7A peak after heating a K-saturated sample for three hours at 550°C . Chlorite was identified by the presence of a 14A peak after 550°C heating. Decreases in the size of the 7A peak with corresponding increases in the 14A peak due to 550°C heating was considered an indication of chlorite, not kaolinite. Some intergrades having intermediate x-ray spacings were observed. Non-crystalline material was considered high in samples with small peaks or none at all.

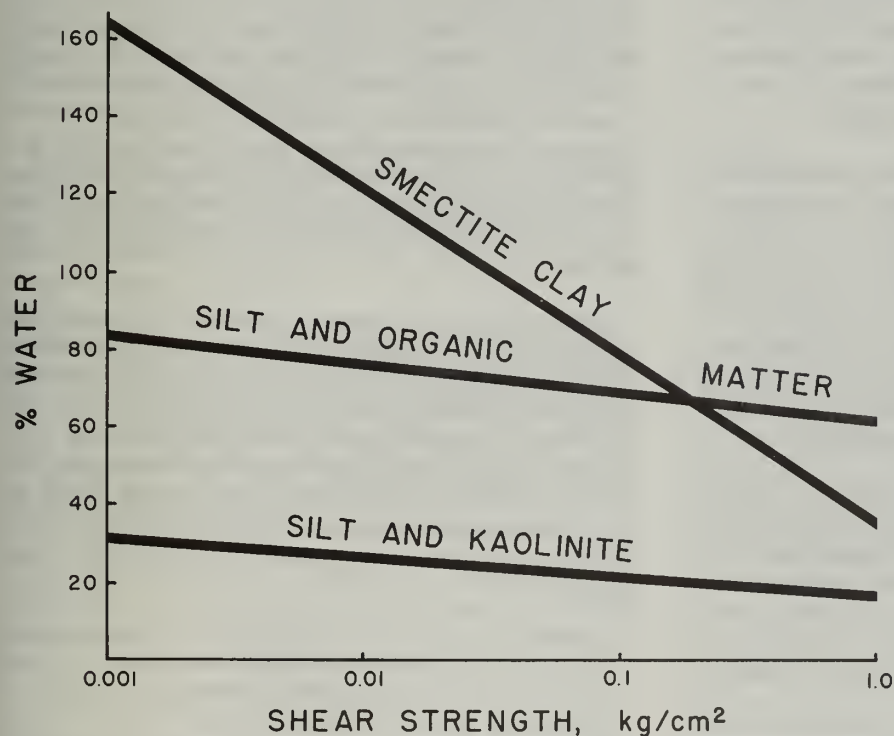


Figure 2. Water content versus shear strength for a landslide soil containing smectite clay (549/72), soil derived from Lambert Siltstone containing large amounts of silt and organic matter (534/72), and a Miocene mudstone containing predominantly silt and kaolinite clay (34/73).

RESULTS AND DISCUSSION

Water versus Shear Strength

The importance of the effect of water content on the shear strength of soils cannot be overemphasized. Any increase in water content will decrease the shear strength of a soil (figure 1). The torsion vane can be used to determine the response of soils and sedimentary rocks to increasing amounts of water. The shear curves determined in this study should be used for comparisons between soils rather than as measures directly applicable to field situations. Results from undisturbed samples would have been different. Also, the rate of water infiltration could not be considered as a factor in these measurements.

The reproducibility of the torsion vane shear test was tested on a very clayey soil from Contra Costa County (figure 1). Two sub-samples from this material gave indistinguishable logarithmic curves (see also Kerr and Drew, 1969). Straight lines were drawn through the extremes of these points. The coefficient of variation was 1.4 percent for the intercept and 3 percent for the slope. Routine analysis of the remaining samples could be done by determining shear strength at only 3 or 4 points at moisture contents between the liquid and plastic limits.

In clayey soils under undrained conditions, internal friction is zero and the torvane shear strength is equal to the cohesive strength. The high intercepts and high negative slopes of clays indicate their cohesive nature and interaction with water. Smectite (formerly the montmorillonite group of clay minerals) is usually the predominant clay mineral in soils with highly sloping shear curves (figure 2).

Silty as well as sandy soils have low intercepts and low slopes (figure 2). This is because cohesion is near zero for sand, and internal friction is unaffected by moisture content. Slopes of shear curves are, therefore, directly related to cohesion. Intercepts would include internal friction as well as cohesion. Kaolinite and other clay minerals with low cation-exchange capacity do not produce steeply sloping curves because their reaction with water is not as great as that of clays such as smectite. The minimum

intercept for sands and silts was 26 percent. This is approximately equal to the theoretical pore space in a well-sorted material.

Effect of Organic Matter

Organic matter contributes considerably to the value for the intercept without apparently affecting the slope of the curve (figure 2). For example, sample 534/72 had very high organic-matter content (about 10 percent) with only traces of kaolinite and mica in the small amount of clay present (table 2). Organic matter increases the natural moisture content of a soil and the amounts of water available to plants. For example, the natural moisture content of this soil was 46 percent on December 11, 1972. The shear strength apparently was increased greatly as a result of soil formation and the accumulation of organic matter. Landslides are rare on soils developed from Lambert siltstone, the formation from which this soil was derived.

This observation appears applicable to establishing vegetation on cut slopes produced during construction projects. The addition of organic matter to unstable soils would increase their water holding abilities. This would make water available to plants over a long period of time, thus encouraging large plants with deep roots to grow and to remove more of the seasonal rainfall. By the end of the dry season, natural moisture contents would be so low that the effect of winter rains on shear strength would be minimized.

Correlations Between Physical Parameters

The large number of samples of varying physical characteristics allowed us to evaluate the relationships between the various physical parameters (table 3). Sand contents are indirectly related to all of the other parameters (silt and clay content, Atterberg limits, and shear strength) as would be expected (i.e., sand, silt, and clay contents total 100 percent). These correlation coefficients were -0.50 or -0.60 except for the plastic limit, which appeared to be more independent of sand contents.

Table 3. Correlation coefficients for physical parameters of soils and sedimentary rocks ($n = 127$ samples).

	% Sand	% Silt	% Clay	Liquid limit	Plastic Limit	Plasticity index	Shear B	Shear M
%Sand ¹	1							
% Silt	-0.50	1						
% Clay	-0.60	-0.40	1					
LL	-0.60	-0.06	0.68	1				
PL	-0.24	0.19	0.08	0.60	1			
PI	-0.60	-0.16	0.78	0.93	0.27	1		
Shear B	-0.61	-0.02	0.67	0.95	0.49	0.92	1	
Shear M	-0.55	-0.05	0.63	0.80	0.25	0.86	0.93	1

¹ The standard physical tests for liquid limit, plastic limit, and shear strength were done on the less than 420 μm material, whereas the particle-size analysis was done on the less than 2000 μm material. To have comparable data for correlations between particle size and the other physical data, the following computations were performed for each sample: clay contents in table 2 were divided by the fraction of sample less than 420 μm . For example, number 574/72 had 38% clay with 12% of the sample in the size range: 2000 - 420 μm . Dividing 38% by $((100 - 12) \div 100)$ gives a value of 43.2% clay in the < 420 μm sample used for determining the plasticity index and shear strength.

Silt contents are slightly more associated with the clayey soils ($r = -0.40$) than with the sandy soils ($r = -0.50$), though both correlations are indirect. The other physical parameters are unrelated to silt contents. In general, the silt fractions in these soils do not contribute to their cohesive character. Cohesion must be derived from minerals occurring only in the clay fractions.

Clay contents are directly correlated with the plasticity index ($r = 0.78$) and liquid limits as well as the intercept and slope of shear curves. These physical properties are all related to each other in some degree, and all reflect the cohesive property of clay.

The liquid limit has an almost direct relationship to the intercept of the shear curve ($r = 0.95$) while its relationship to the slope of shear curves was somewhat less direct ($r = 0.80$). Perhaps this is because any organic matter present in a soil sample may contribute to an increase in the liquid limit and intercept without changing the slope of the shear curve (figure 2).

The plastic limit, though slightly correlated with the liquid limit ($r = 0.60$), appears to be one of the most independent of the physical parameters. The plasticity index, however, was highly correlated with the intercept ($r = 0.92$) and slope ($r = 0.86$) as well as the liquid limit ($r = 0.93$) from which it is partly derived. In each case, the intercept of the shear curve was more closely related to cohesive properties than to the slope. Still, correlations between the parameters denoting cohesion and the amount of clay can account for only half the variance. We have shown that increasing sand contents lead to decreasing cohesion but that increasing silt contents have no effect upon cohesion. Perhaps, variations in the type of clay can account for some of the variation in correlations between clay contents and cohesion.

Clay Mineralogy

Correlations With Physical Parameters

Rather pure samples of montmorillonite (a smectite) can have liquid limits up to 500. Thus, it is not surprising that clay contents of soils high in montmorillonite would be directly related to physical parameters such as liquid limits. It is difficult, however, to attribute high liquid limits of soils to a specific mineral such as smectite because soils are composed of a mixture of minerals. A quantitative determination of the clay minerals in a soil would be ideal for determining relationships between clay mineralogy and physical parameters. Lacking this information, qualitative x-ray diffraction data were used to estimate the relative amounts of the various clay minerals in the less than 2 μm fractions. Samples were classified into four groups: 0 for no clay minerals detected, 1 for trace amounts present, 2 for moderate amounts present, and 3 for abundant amounts present (table 2). These values were multiplied by the fraction of clay found in the material tested (see footnote, table 4).

Table 4. Coefficients for correlations between physical parameters and relative amounts of clay minerals ($n = 127$ samples).¹

	Liquid limit	Plastic limit	Plasticity index	Shear B	Shear M
Smectite	0.70**	0.16	0.77**	0.69**	0.63**
Montmorillonite	0.46**	-0.03	0.57**	0.51**	0.51**
Beidellite	0.42**	0.09	0.47**	0.36**	0.30**
Vermiculite	-0.09	-0.15	-0.04	-0.10	-0.07
Chlorite	0.21*	-0.08	0.28**	0.24*	0.33**
Kaolinite	0.04	-0.11	0.09	0.06	0.10
Mica	0.18	-0.04	0.23*	0.19	0.25**
Noncrystalline	-0.04	0.13	-0.13	-0.13	-0.19

¹ The relative amount of a particular clay mineral in the sample used for physical testing was calculated as follows. First, it was assumed that the clay minerals exist only in the clay fractions. Second, the particle size data was corrected for less than 420 μm material as in footnote 1, table 3. Third, this corrected value for clay content (43.3 percent in the example of footnote 1, table 3) was multiplied times the relative amount of clay mineral in the sample used for x-ray diffraction. For example, if smectite was the dominant mineral in the clay fraction, the relative amount of smectite in the clay would be 3. Consequently, the relative amount of smectite in the sample used for physical testing would be this (3) times the amount of clay (43.3 percent). This results in a value of 1.3, reflecting the diluting effects of sand and silt.

* Correlation coefficient greater than 0.20 (significant at the 5% level).

** Correlation coefficient greater than 0.25 (significant at the 1% level).

Regression analysis of these values and the physical parameters shows that there is no consistent relationship between the plastic limit and variations in the types of clay minerals (table 4). Smectite (montmorillonite and beidellite) is directly related to the liquid limit ($r = 0.70$), plasticity index ($r = 0.77$, figure 3), and the intercept ($r = 0.69$) and negative slope ($r = 0.63$) of shear curves. Chlorite and mica each account for less than 10 percent of the variance in correlations with physical parameters. Vermiculite, kaolinite, and non-crystalline material (determined by absence of an x-ray diffraction pattern) were unrelated to any of the physical parameters in this study.

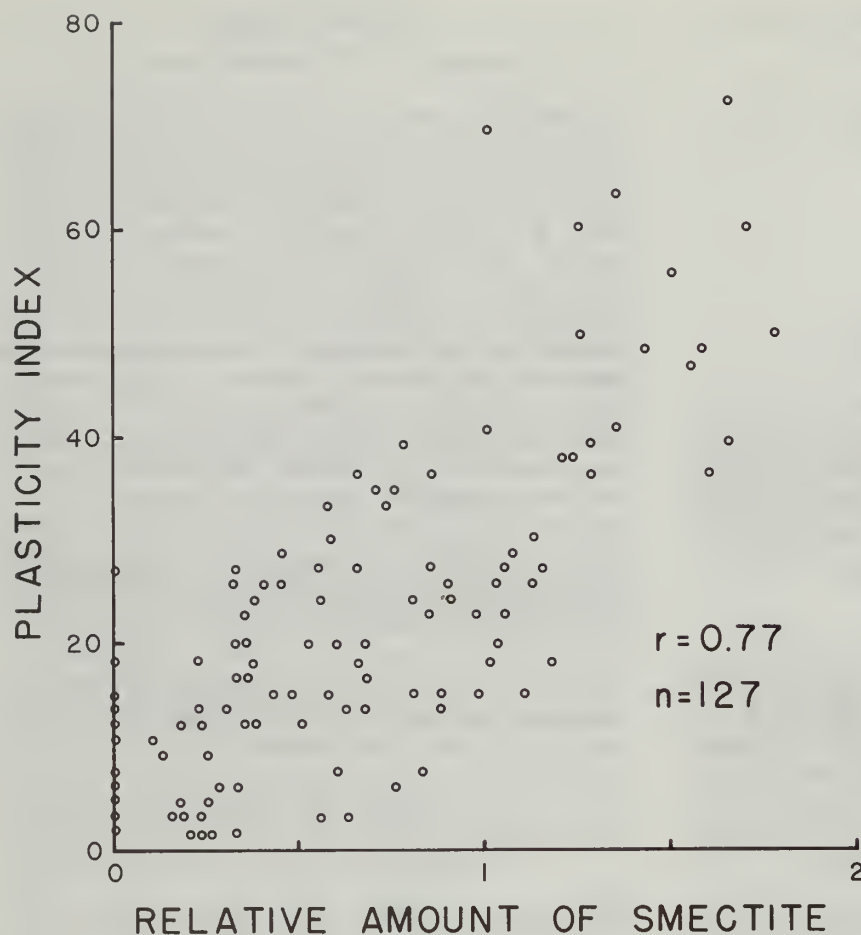


Figure 3. Relationship between the plasticity index and smectite.

The cohesive character of these soils appears to be determined by essentially one mineral—smectite. The other expanding clay mineral, vermiculite, does not contribute significantly to measures of cohesion. The reasons for this remain obscure. However, many noncohesive type slides in Marin County, for example, occur in soils developed from schists. These soils contain a great deal of vermiculite derived from coarse-grained micas. Schist-derived soils appear to be involved in numerous landslides, but soil expansion doesn't seem to be a significant problem.

Two different types of smectite can be seen in x-ray diffraction patterns of clays. Montmorillonite tends to have a slightly more expansive character than beidellite, the other common smectite in soils (Borchardt, 1977a). Montmorillonite, for example, is more highly correlated with the plasticity index than beidellite (table 4). The differences between these two smectites is even greater for the correlations involving the intercepts and slopes of shear curves. Perhaps this is an indication that beidellitic soils are less expansive and less likely to be involved in landslides than montmorillonitic soils. Further work on quantitative methods of distinguishing between these two minerals and their relationship to physical properties may help to explain some of the variations included under the group name "smectite".

Correlations Among Clay Minerals

Correlations among the clay minerals themselves gave hints of possible relationships (table 5). Of particular interest is the correlation of $r = 0.38$ between beidellite and chlorite. Beidellite was the only clay mineral detected in a soil derived from chloritic greenstone (520/72, table 1 and 2). On the other hand, the correlation between montmorillonite and chlorite was not significant, suggesting that montmorillonite must form in an environment different from beidellite.

Table 5. Correlations among estimates of clay mineral contents ($n = 127$ samples).

Clay mineral	St	Mt	Bd	Vr	Ch	Kl	Mi	Nc
Smectite	1							
Montmorillonite	0.54 ²	1						
Beidellite	0.79 ²	0.12	1					
Vermiculite	-0.11	-0.25 ²	0.02	1				
Chlorite	0.35 ²	0.12	0.38 ²	-0.09	1			
Kaolinite	0.04	0.09	0.09	0.11	0.11	1		
Mica	0.15	0.16	0.06	0.22 ¹	0.30 ²	0.20 ²	1	
Noncrystalline	-0.22 ¹	-0.15	-0.16	-0.09	-0.16	0.02	-0.12	1

¹ $r = 0.20$ significant at 5% level

² $r = 0.25$ significant at 1% level

Expansive Soils

The plasticity index may be used as an estimate of the swelling potential of a soil (Pettry and Rich, 1971). Consequently, the direct correlation between the plasticity index and smectite contents confirms other observations that smectite is a necessary ingredient in soil expansion and soil creep (Borchardt, 1977a). Other clay minerals expand much less and even vermiculite seems to contribute very little to plasticity.

Soils and sediments containing large amounts of smectite obviously pose a threat to structures in direct proportion to the amount of smectite present. However, engineers have little need for quantitative clay mineralogical data for expansive soils. It is much easier to measure the potential for soil expansion directly. Landslide potential, however, is not so easily measured.

Landslides

Landslides may occur in soils of all types, but we first wanted to see if some of the common physical parameters might distinguish between stable and unstable materials. Sixty-six samples from landslides were selected for evaluation. Plots (data not shown) of plasticity index *versus* % clay $\div$ (% clay + % sand) and plasticity index *versus* % smectite $\div$ (% smectite + % sand) were made to see if there is a natural distinction between "cohesive" and "noncohesive" landslides. In these plots, the clay or smectite content represents the cohesive property and the sand content represents the noncohesive property of landslides.

The plasticity index, sand, clay and estimated smectite contents each varied over wide ranges. No natural discon-

tinuity could be found to separate landslides into cohesive and noncohesive types. Any such distinctions would have to be purely arbitrary.

The Unified Soil Classification system further reveals the widely varying character of the 66 landslide samples (figure 4). The data for some of these samples could be plotted in each of the major portions of the graph. Landslides of the Coast Ranges may be classed as CH (clays of high plasticity), CL (clays of medium and low plasticity), ML (silts of medium and low compressibility), and even MH (silts of high compressibility). Obviously, the plasticity index (or other variables related to cohesion such as smectite content, liquid limit, or intercept and slope of shear curves) is of little use in the detection of slope stability. Likewise, slope stability is not a simple function of the content of any particular clay mineral.

Each of the clay minerals was found in at least one of the 66 landslide soil samples. The absence of any one of these clay minerals would thus not indicate a stable soil. Combinations of clay minerals can often indicate environments of formation. Perhaps a unique pair of clay minerals could be found that doesn't occur in landslides. An evaluation of the clay mineralogical data in table 2 showed that all combinations (e.g., kaolinite-mica, kaolinite-smectite, etc.) were represented in at least some of the landslide samples. Occasionally, the absence of a particular mineral when another is present may indicate genetic information associated with the environment of formation. In turn, this may reveal a sedimentary deposit unique for its stability.

Two minerals giving this possibility are kaolinite and smectite. Kaolinite forms in soils under a highly leached, well-drained, low-pH environment. Smectite, on the other hand, forms under a poorly-drained, high-pH envi-

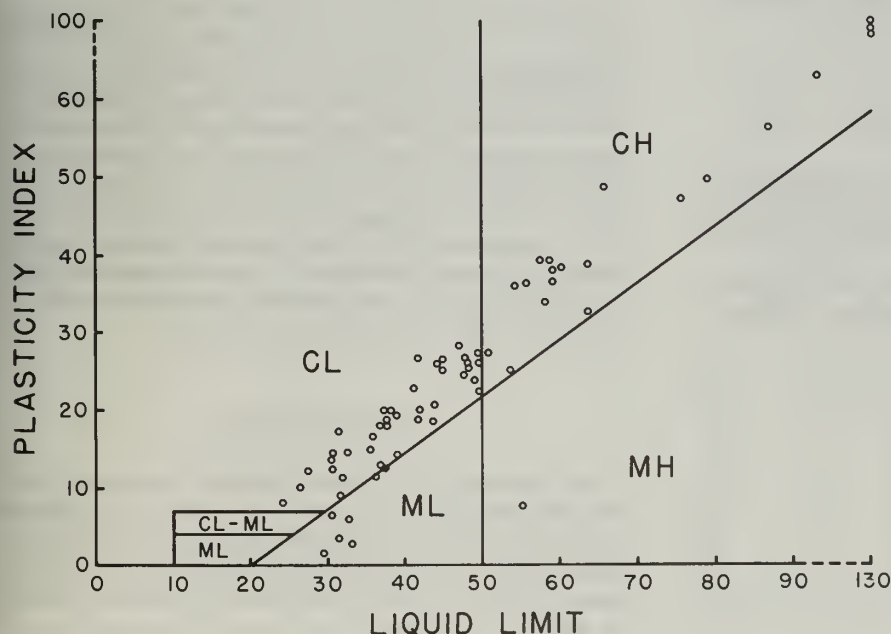


Figure 4. Unified soil classification for 66 landslide samples.

ronment (Borchardt, 1977a). The landslide soil samples were evaluated for pairs of clay minerals in which one clay mineral was present while the other was absent. At least one representative of each present-absent pair was found except for the pair: kaolinite without smectite. To put it another way, we were unable to find a smectite-free kaolinitic landslide.

Each of the 28 landslide samples containing kaolinite had smectite as well. In addition, 10 of these had no detectable amounts of chlorite. This is important because the positive identification of kaolinite in the presence of chlorite is often very difficult by the x-ray methods used here.

Possibly, kaolinitic clays that are free of smectite would indicate rather stable soils and sedimentary rocks. Indeed, this appears to be the case for samples 534/72, 567/72, 568/72, and 31/73 (tables 1 and 2). Each of these Tertiary mudstones or siltstones has been judged to be relatively stable (Rogers and Armstrong, 1973; Huffman, 1972). These rocks, however, comprise a very limited area in the Coast Ranges. They may have been deposited as turbidites eroded from a landmass consisting almost entirely of granitic rocks from the west side of the San Andreas fault (Wentworth, 1968). These granites had large amounts of biotite and K-feldspar. Both minerals weather to kaolinite under humid conditions. Smectite, on the other hand, more commonly forms from volcanic rocks (Borchardt, 1977a) that form a significant part of the Franciscan rocks that dominate the remainder of the Coast Ranges.

Other soil samples had "kaolinite" without smectite (559/72, 11/73, and 29/73), but the presence of chlorite makes the identification of "kaolinite" uncertain. If the need arises, special methods can be used to distinguish between kaolinite and chlorite (Brown, 1961). The observation that landslides do not occur in soils containing smectite-free kaolinite needs further testing.

Summary of the Clay Mineralogy of Landslides

In general, smectite dominated the clay mineralogy of the 66 samples known to represent landslides of coastal California (table 6). Over 90 percent of the samples had

Table 6. Relative abundance of minerals in clay fractions extracted from 66 landslide samples of coastal California.

Landslides having the following amounts of each mineral:				
Clay mineral	Abundant	Moderate	Trace	None
Smectite ¹	60%	18%	14%	8%
Montmorillonite	29	15	11	45
Beidellite	39	15	23	23
Vermiculite	11	20	23	46
Chlorite	2	15	44	39
Kaolinite	0	15	27	58
Mica	0	3	68	29

¹ Smectite includes beidellite and/or montmorillonite, whichever was most abundant.

at least traces of smectite with 60 percent of these having abundant amounts. Among the smectites, beidellite appears to be slightly more common in these landslides than montmorillonite. This could be a result of the transformation of beidellite from mica (Borchardt, 1977a), a mineral which was also found in over two-thirds of the landslides.

Even the five landslides without detectable smectite had expanding clay, namely vermiculite. Vermiculite occurred in half of the samples and was particularly abundant in 11 percent of them. Moderate to trace amounts of chlorite were found in over 60 percent of the samples. This was primarily mafic chlorite from the original parent rock. Mafic chlorite was indicated by decreases in second order and increases in first order basal spacings as a result of heating samples at 550°C. Moreover, there was very little evidence for pedogenic chlorite which can form in soils as a result of interlayering of smectite or vermiculite.

About 60 percent of the landslide samples had no detectable kaolinite. Traces were found in 27 percent of the samples, and moderate amounts were found in 15 percent of the samples. Neither kaolinite nor mica were abundant in any of the landslides (table 6).

Monitoring Unstable Slopes

Smectite and its cohesive property appears to be the primary determinant of the rate of response to increases in moisture (figure 2). Poorly drained smectitic soils will lose shear strength as a result of low rates of rainfall, while well-drained, sandy soils will not. Nevertheless, sandy soils may suddenly lose strength as a result of high rates of rainfall. Presumably, soils with intermediate characteristics would respond similarly to intermediate rates of rainfall.

This leads to practical applications concerning warning systems for monitoring unstable slopes. Campbell (1975) has suggested that this is well within present technological capabilities. Moisture contents of soils and sedimentary rocks could be continuously monitored. The data could then be applied to knowledge about the soil-water system like that obtained for plotting shear curves such as in figure 1. Soil moisture levels could be constantly monitored at various depths of overburden. Warnings could be sounded whenever the increase in moisture content threatened to decrease the shear strength below that capable of supporting the corresponding overburden.

CONCLUSIONS

One hundred twenty-seven soil and sedimentary rock samples were used to evaluate the relationships between various parameters commonly used to describe the physical properties of soils. Specifically, the following variables appear directly related to each other: liquid limit, plasticity index, clay content, intercept and negative slope of

shear strength curves, and smectite content (montmorillonite or beidellite). Unrelated variables include: plastic limit, vermiculite, chlorite, kaolinite, and mica. In general, the correlated variables all indicate soils or geologic formations containing smectite and likely to be unstable.

Sixty-six samples known to represent landslides had widely ranging physical properties, none of which could be used to distinguish them from stable slopes. Ninety percent of the landslides had smectite which was particu-

larly abundant in 60 percent of them. Although five landslide samples were void of smectite, they contained vermiculite, the other expanding clay mineral. Traces of nonexpanding clay minerals, mica and chlorite, were found in over two-thirds of the landslides. Kaolinite, however, was not found in 60 percent of the landslides.

Slopes containing smectite-free kaolinite appeared to be stable. These were represented by Tertiary mudstones found on the west side of the San Andreas fault.

REFERENCES

- Alfors, J.T., Burnett, J.L., and Gay, Jr., T.E., 1973, Urban geology master plan for California: California Division of Mines and Geology Bulletin 198, 112 p.
- Bishop, C.C., Knox, R.D., Chapman, R.H., Rodgers, D.A., and Chase, G.B., 1973, Geological and geophysical investigations for tri-city seismic safety and environmental resources study: California Division of Mines and Geology Preliminary Report 19, 44 p.
- Borchardt, G.A., 1977a, Montmorillonite and other smectite minerals, in J.B. Dixon, and S.B. Weed, editors, Minerals in soil environments: Soil Science Society of America, Madison, Wisconsin, p. 293-330.
- Borchardt, Glenn, 1977b, Physical testing of soils for urban development: California Division of Mines and Geology, California Geology, v. 30, p. 254-258.
- Brown, G., 1961, editor, The x-ray identification and crystal structures of clay minerals: Mineralogical Society, London, 544 p.
- Brown, G., and Farrow, R., 1956, Introduction of glycerol into flocculants by vapour pressure: Clay Minerals Bulletin, v. 3, p. 44-45.
- Campbell, R.H., 1975, Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California: U.S. Geological Survey Professional Paper 851, 51 p.
- Cosagrande, A., 1932, Research on the Atterberg limits of soils: Public Roads, v.13, p. 121-130, 136.
- Chu, T.Y., and Davidson, D.T., 1953, Simplified air jet dispersion apparatus for mechanical analysis of soils: Proceedings of the Highway Research Board, v. 32, p. 541-547.
- Doy, P.R., 1965, Particle fractionation and particle size analysis, in C.A. Black, editor, Methods of soil analysis: American Society of Agronomy, Madison, Wisconsin, p. 545-567.
- Horwood, M.E., and Brindley, G.W., 1964, Swelling properties of synthetic smectites in relation to lattice substitutions: Clays and Clay Minerals, v.13, p. 209-222.
- Huffman, M.E., 1972, Geology for planning on the Sonoma County coast between the Russian and Gualala Rivers: California Division of Mines and Geology Preliminary Report 16, 38 p.
- Huffman, M.E., with Chase, G.B., Smith, T.C., and Greensfelder, R.W., 1973, Geology for planning on the Sonoma County coast between Russian River and Estero Americano: California Division of Mines and Geology Preliminary Report 20, 38 p.
- Kerr, P.F., and Drew, I.M., 1969, Clay mobility, Portuguese Bend, California, in Short contributions to California geology: California Division of Mines and Geology Special Report 100, p. 3-16.
- Petty, D.E., and Rich, C.L., 1971, Modification of certain soils by calcium hydroxide stabilization: Soil Science Society of America Proceedings, v. 35, p. 834-838.
- Rice, S.J., 1973, Geology and geologic hazards of the Novato area, Marin County, California: California Division of Mines and Geology Preliminary Report 21, 47 p.
- Rogers, T.H., and Armstrong, C.F., 1973, Environmental geologic analysis of the Monte Bello Ridge study area, Sonoma County, California: California Division of Mines and Geology Preliminary Report 17, 52 p.
- Sawers, G.F., 1965, Consistency, in C.A. Black, editor, Methods of soil analysis: American Society of Agronomy, Madison, Wisconsin, p. 391-399.
- Theisen, A.A., and Horwood, M.E., 1962, A paste method for preparation of slides for clay mineral identification by x-ray diffraction: Soil Science Society of America Proceedings, v. 26, p. 90-91.
- Wentworth, C.M., 1968, Upper Cretaceous and lower Tertiary strata near Gualala, California, and inferred large right slip on the San Andreas fault, in W.R. Dickinson and Arthur Grantz, editors, Proceedings of conference on geologic problems of San Andreas fault system: Stanford University Publication, Geological Sciences, v.11, p. 130-143.

THIS BOOK IS DUE ON THE LAST DATE
STAMPED BELOW

BOOKS REQUESTED BY ANOTHER BORROWER
ARE SUBJECT TO RECALL AFTER ONE WEEK.
RENEWED BOOKS ARE SUBJECT TO
IMMEDIATE RECALL

~~JUN 30~~ 1988

RECEIVED

MAR 11 1988

PHYS SCI LIBRARY

JUN 1 1988
RECEIVED

JUN 21 2001

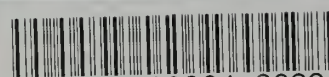
Physical Sciences Library

LIBRARY, UNIVERSITY OF CALIFORNIA, DAVIS

D4613 (12/76)

MAY 25 '83

MAY 31 '83



3 1175 00364 2629

